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FLAME STRAIGHTENING QUENCHED-AND-TEMPERED STEELS IN SHIP CONSTRUCTION

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Battelle Columbus Laboratories

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Ship Structure Committee

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From a previous Ship Structure Committee sponsored laboratory investigation, guidelines evolved for flame straightening distorted weldments in shipyards. Validating these guidelines required the cooperation and some financial support from a shipyard to reproduce and revise the procedures for shipyard use.

The Ship Structure Committee was fortunate to be able to join with Avondale Shipyards, Incorporated, to undertake this task and to report the results in this document.

Comments on this report and suggestions for additional research topics will be most welcome.

W. M. Benkert
Rear Admiral, U.S. Coast Guard
Chairman, Ship Structure Committee

20. ABSTRACT (Cont.)

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Flame straightening quenched-and-tempered steel procedures were successfully employed by trained shipyard personnel on portions of a LASH (Lighter Aboard Ship) ship under construction with minimal acceptable loss in mechanical properties and with considerable savings in time and money. Test checks were conducted in the laboratory with simulated experiments on steel panels 150 inches by 48 inches by 5/16 inch and stiffened by angles at 30-inch

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on

Project SR-212, "Shipyard Forming Parameter Study"

FLAME STRAIGHTENING QUENCHED-AND-TEMPERED STEELS IN SHIP CONSTRUCTION

by

R. L. Rothman

Battelle Memorial institute

under

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Washington, D.C.
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ABSTRACT

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INTRODUCTION

Traditionally, shipyards have relied on flame straightening to remove weld distortion in the case of hot-rolled steels. These steels are very forgiving in that accidental overheating does not damage the material easily. The more recent interest in the use of quenched-and-tempered steels for ship structures has posed new questions on whether flame straightening may still be used. The basis for these questions lies in the fact that the quenched-and-tempered steels derive their superior mechanical properties from heat treatment, and further heating can cause deleterious effects in strength and toughness.

Investigations have been sponsored by the Ship Structure Committee to evaluate the effect of flame straightening on the mechanical properties of quenched-and-tempered steel and a tentative procedure has been drawn up. By controlling the heating conditions to limit the surface temperature to a maximum of 1050 F, no significant reduction in strength and toughness is to be expected. Within this temperature limitation considerable straightening can be achieved. The following recommended procedure has been used in the shipyard on portions of a LASH ship under construction to remove distortions of up to 3/8-inch bow in a portion of the structure consisting of 5/16-inch stiffened panels 150 inches by 48 inches.

RECOMMENDED PROCEDURE FOR FLAME STRAIGHTENING QUENCHED-AND-TEMPERED STEEL

Heating should be done on the high side of the plate and at the location of maximum height. In the case of stiffened panels, this most frequently corresponds to the reverse side of the plate from the stiffener weld.

Since the principal cause of distortion is welding, the general outline of the distorted regions tends to be parallel to welds. Line heating is most effective in flame straightening this distortion. Spot heating is also useful in certain situations and is conducted under the same general conditions as line heating.

Thickness

Flame straightening of quenched-and-tempered steels has been conducted on 5/16-inch and 1/2-inch plate. In principle, it can be

performed on any thickness plate although temperature control will be a problem for very thin plates, and plate stiffness will become a major factor for thick ones.

Equipment

The heating torch can vary depending on operator preference as can the fuel gas. The water quench should be coupled to the torch for ease of handling. Either an annular or single stream quench can be used.

Temperature Measurement

Temperature-indicating crayons melting at 900 F and 1050 F should be mounted in a single holder so that both can be applied simultaneously to the heated surface. The temperature should be checked immediately after removal of the flame and in the location of last heating after approximately 12 inches of travel.

Preparation

The preparation required is identical to that followed in flame straightening hot-rolled steels. Initially, make an estimate of the unfairness and decide which panels have the greatest distortion and which are acceptable as is. Select the high regions and mark lines along the maxima so they can be followed easily by the torch operator.

Straightening

Heat the lines marked previously maintaining a continuous quench behind the torch. Torch speed should typically be 24 to 30 inches per minute; however, this will vary with such factors as the torch, gas flow, and plate thickness. The important criterion is temperature, and this should be checked periodically by removing the torch and applying the temperature-indicating crayons simultaneously and quickly. The 900 F crayon should melt, but the 1050 F one should not. As an additional check on temperature, no obvious color should be visible immediately after removing the torch. Such choices as whether to work upwards or downwards on a bulkhead will depend on the particular equipment being used and should be made by the operator.

Sequence

Heat the lines with greatest distortion first using one pass per line. Then, check the unfairness and proceed to the less

distorted lines, if necessary. If further straightening is required after completing one pass per line, heat additional lines approximately one inch to the side of the initial lines.

BACKGROUND

This program was undertaken to complete the laboratory development of flame-straightening techniques for quenched-and-tempered steels and to demonstrate its success in the shipyard.

For years, shipyards have relied on flame straightening to remove the welding distortion introduced during fabrication in the case of hot-rolled steels. These steels are relatively forgiving with regard to flame-straightening temperatures and consequently the process can be applied to them at the discretion of the yard. Quenched-and-tempered steels, on the other hand, develop their mechanical properties* through controlled heat treatments, and consequently these properties can be impaired by exposure to high temperatures during fabrication. Flame straightening of quenched-and-tempered steels is currently forbidden for this reason. Alternatives to flame straightening for distortion removal are the use of mechanical force and panel removal followed by rewelding. In rare cases, the application of extra bead-on-plate welds has been permitted.

Consequently, programs have been conducted to determine under what limitations flame straightening could be applied to quenched-and-tempered steels. The results of the program preceding this one** showed that quenched-and-tempered steels could withstand, without deleterious effects, temperatures as high as 1300 F for the short time periods required for flame straightening. Techniques were then developed for flame straightening heavily restrained plates 48 inches by 48 inches by 1/2 inch, and it was demonstrated that flame straightening could be used successfully on these steels with no loss in mechanical properties. The panels used in the present program were thinner (5/16 inch), larger (150 inches by 48 inches), and were stiffened by angles at 30-inch intervals.

With the ultimate objective of this program being the application of flame-straightening procedures in a shipyard, the developmental laboratory work was planned to be as relevant as possible to shipyard practice. Accordingly, laboratory procedure development was conducted on panels essentially the same as those being used on a LASH (Lighter Aboard Ship) ship now under construction with regard to steel, panel size, thickness, and stiffener spacing. First, simulation experiments

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* The particular properties of interest in this program are strength and toughness.

** "Effect of Temperature and Strain Upon Ship Steels", SSC Report 235, by R. L. Rothman and R. E. Monroe, 1973.

proved that the steels under study could be given the thermal cycles required for flame straightening with no loss in properties. Then, once the procedures had been developed in the laboratory in conjunction with Avondale Shipyard personnel, flame straightening was conducted successfully in the yard, and the economic advantages over alternative straightening processes were documented.

The steel used through both the laboratory and shipyard phases of the program was Armco QTC and it was purchased directly from the shipyard. The heat treatment was to austenitize at 1650 F, quench, and temper at 1120 F. Different heats of material were used in the laboratory and the shipyard. The chemical analysis of the laboratory material was given by the mill test report as

C	Mn	P	S	Si	Cr	Ni	Mo	Cu
0.17	1.47	0.011	0.028	0.43	0.19	0.22	0.07	0.23

SIMULATION EXPERIMENTS

Experiments were performed in which heating cycles representative of flame straightening were given to the steel under completely controlled conditions. If the steel showed any loss in properties as a result of these simulations then the effect of flame straightening would have to be at least as great. On the other hand, if no loss in properties resulted from the simulation experiments, then it would be known that the steel could be given a time-temperature cycle representative of flame straightening with confidence and, should any degradation occur due to flame straightening, it would have to be caused by overheating.

Simulation Procedures

The simulation experiments were conducted on the Gleeble which has the capability to reproduce the desired time-temperature cycle accurately. It uses resistance heating so that the temperature is uniform through the thickness. The procedures followed are described in detail in SSC-235 and are summarized in this report.

The thermal cycle used consisted of a 15-second linear rise to the peak temperature, a 15-second hold at temperature, and finally a water quench for cooling. Peak temperatures of 900 F, 1100 F, and 1300 F were used. No load was applied to simulate restraint. A total of two tensile samples and twenty-four Charpy V-notch samples were

prepared at each of the three peak temperatures for subsequent testing. Because of the thickness of the steel (5/16), two-thirds size Charpy V-notch samples were used throughout the program. All samples were taken parallel to the rolling direction of the plate.

Simulation Results

The results of the simulation experiments are summarized in Table 1. Tensile results are reported in terms of yield strength, tensile strength, and elongation in 2 inches. Charpy results are reported in terms of upper shelf energy and the temperature at which 50 percent of the upper shelf energy was absorbed (T_{50}). The lower shelf energy was not reached at test temperatures as low as -180 F. The Charpy data represent the results of testing three samples at each of eight test temperatures.

The tensile and Charpy results show no loss in any measured property as a result of the flame-straightening simulations.

Simulation Conclusions and Significance to Subsequent Work

From the results of the simulation experiments, it is concluded that no loss in properties will occur as a result of flame straightening at peak temperatures as high as 1300 F. Consequently, the actual flame-straightening experiments could be undertaken knowing that a reduction of properties could occur only if the plates were heated to higher temperatures. Practical considerations of temperature measurement in a shipyard dictate that a margin of safety be included in the setting of an operational temperature range for production work. Hence, in line with the work described in SSC-235, it was decided to use the temperature range 900 F $\leq$ T $\leq$ 1050 F for all flame straightening.

LABORATORY PANEL EXPERIMENTS

Flame-straightening experiments were conducted in the laboratory on full-size panels to develop the procedures and experience necessary to perform subsequent work in the shipyard. Initial work was performed entirely by Battelle-Columbus personnel. Once the process development had been completed and straightening could be accomplished reproducibly, Avondale personnel came to Battelle-Columbus to familiarize themselves with the methods used. Subsequently, they trained workers at Avondale so that the shipyard work which followed could be done by production personnel.

TABLE I. RESULTS OF FLAME STRAIGHTENING SIMULATIONS ON QTC MODIFIED STEEL

Treatment Temperature (F), Time (Sec.)	2/3 Size Charpy Results Upper Shelf (ft-lb)	T_{50} (F)	Tensile Results σ_y (ksi)	Elongation (% in 2 in)	σ_T(ksi)
As-Received	29.0	-161	94.8	20.0	108.0
900, 15, Quench	28.5	-169	96.3	22.0	107.5
1100, 15, Quench	29.0	-175	95.6	21.5	107.5
1300, 15, Quench	30.0	<-182	98.7	20.5	108.5

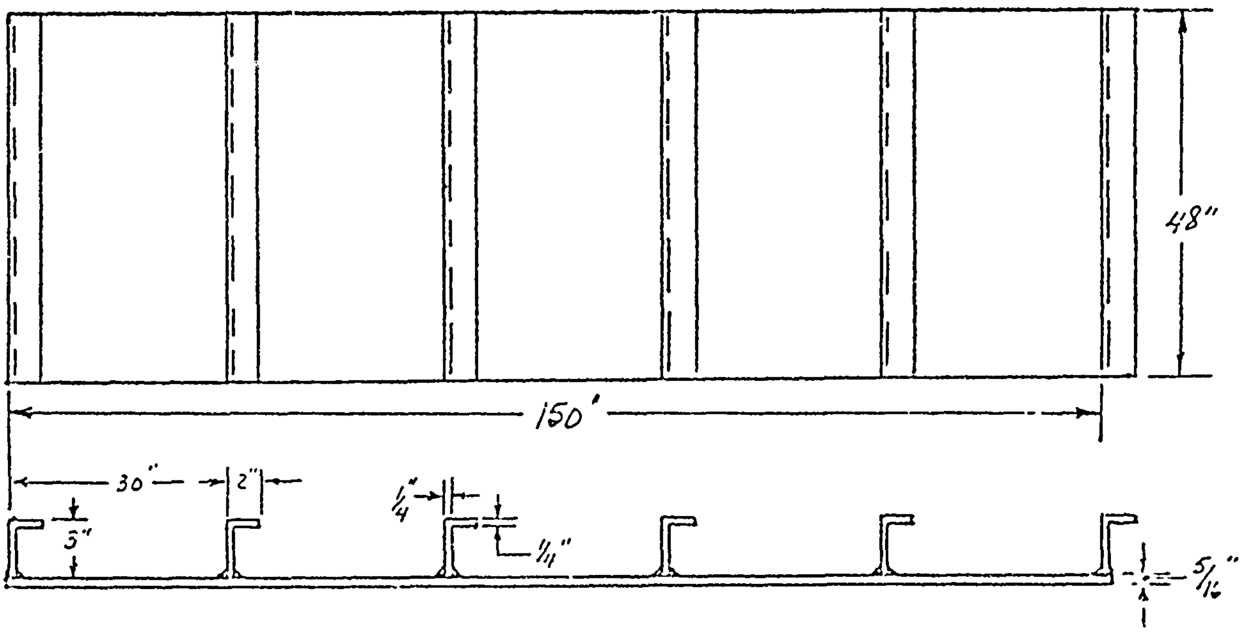

FIGURE 1 - TEST PANEL

Laboratory Panel Procedures

The panel used for the laboratory phase of the program is shown in Figure 1. The steel, plate thickness, angle size, and angle spacing are identical to that on the LASH ship structure. The only difference was that the experimental panel was not restrained around the periphery as an actual structure would be.

The angles were welded using E10018M electrodes. Although one pass on each side would be normal fabrication practice, two passes per side were used in this program in order to increase the distortion. The as-welded panels contained an end-to-end bowing distortion of approximately 2 inches over the 150-inch length and a stiffener-to-stiffener "oil-can" distortion of 0.2 to 0.4 inch.

A reference frame constructed of I-beams and bar stock was used for all measurements which were made by dial gage. They were made on the reverse side of the plate from the stiffeners at the stiffener locations and midway between them over the middle 10 feet of the panel.

The flame heating was done using an oxyacetylene torch with an Oxweld 100 A3 tip. In accordance with the results of SSC-235, the plate was heated to an operating temperature range of greater than 900 F and less than 1050 F as measured by temperature-indicating crayons. The 900 F and 1050 F crayons were mounted in a single fixture so that both could be applied simultaneously. The temperature was measured every 12 inches immediately after the flame had been removed. The water-quench line was coupled to the torch so that both could be applied with one hand by the operator. The quench was applied approximately two inches behind the flame. Since the heating process was controlled on the basis of steel surface temperature the specification of torch and flame characteristics such as standoff distance, gas-flow rates, and travel speed was unnecessary.

Previous direct experience with flame straightening, reported in SSC-235, had involved work on heavily restrained panels 48 inches by 48 inches by 1/2 inch. It was determined that spot heating provided the best control as a method of heat application for that panel and it was therefore used to do the flame straightening. In addition to the plate size and restraint, the 48-inch panels differed from those studied in this program (Figure 1) in that butt welds for the previous panels were made around the panel periphery so that the high area occurred in the panel center. Since it was recognized that flame straightening should begin at the convex surfaces, no heating was done around the welds since they were low points. In contrast, the panels used in this program contained six double-fillet welds and, since the reverse side of each was a convex (or high) area, straightening was begun at the stiffener locations. Furthermore, since the convex regions ran parallel to the welds, line

heating matched the general outline of the distorted regions and was applied to the panels. It worked so well that, except for isolated experimentation with spot heating for comparative purposes, all straightening was done by line heating.

A typical example of the results obtained by flame straightening in this program is shown in Figure 2. This is a plot of panel height as a function of distance along the panel measured along the midpoint (24 inches from the ends). The as-welded profile shows both the bowing distortion and the localized oil-canning distortion with maxima at the stiffeners. The overall bowing distortion was removed by heating three lines over each stiffener -- one line centered at the stiffener and one an inch to either side. Three lines were required because the panel had been overwelded to increase the distortion.

The results of subsequent line heating for removal of the oil-can distortion are also shown in Figure 2. The lines heated were both some repeats of lines heated in removing bowing distortion and some additional lines placed closely to previous ones. The rule followed in selecting line placement was to heat where the plate was high. The lines were done one at a time so that the effect of each could be observed before proceeding. Referring to Figure 2, the following lines were required to remove the oil-can distortion after the bowing distortion had been removed:

Two along the stiffener at 30 inches
One along the stiffener at 60 inches
Three along the stiffener at 90 inches
Three along the stiffener at 120 inches.

The final profile had a total variation in height of 0.15 inch over the 150-inch panel length. This level of flatness far exceeds any required in construction, and the effort to obtain this flatness was made only to learn the capabilities of flame straightening.

Straightening was done by the same techniques both when the panel was lying on the floor and when it was hanging vertically as held by a crane.

Spot heating was used in addition to line heating on selected panels to compare the two processes. Spot heating was not used exclusively on any panel but was only applied in a localized region. The distortion was such that the convex area always occurred between the stiffeners on the opposite plate side from the stiffener to plate welds. Distortion removal is usually more conveniently done on this side rather than on the side of the stiffeners. When spot heating was used, it was done on the stiffener side of the panel. Line heating was both much faster and gave greater distortion removal.

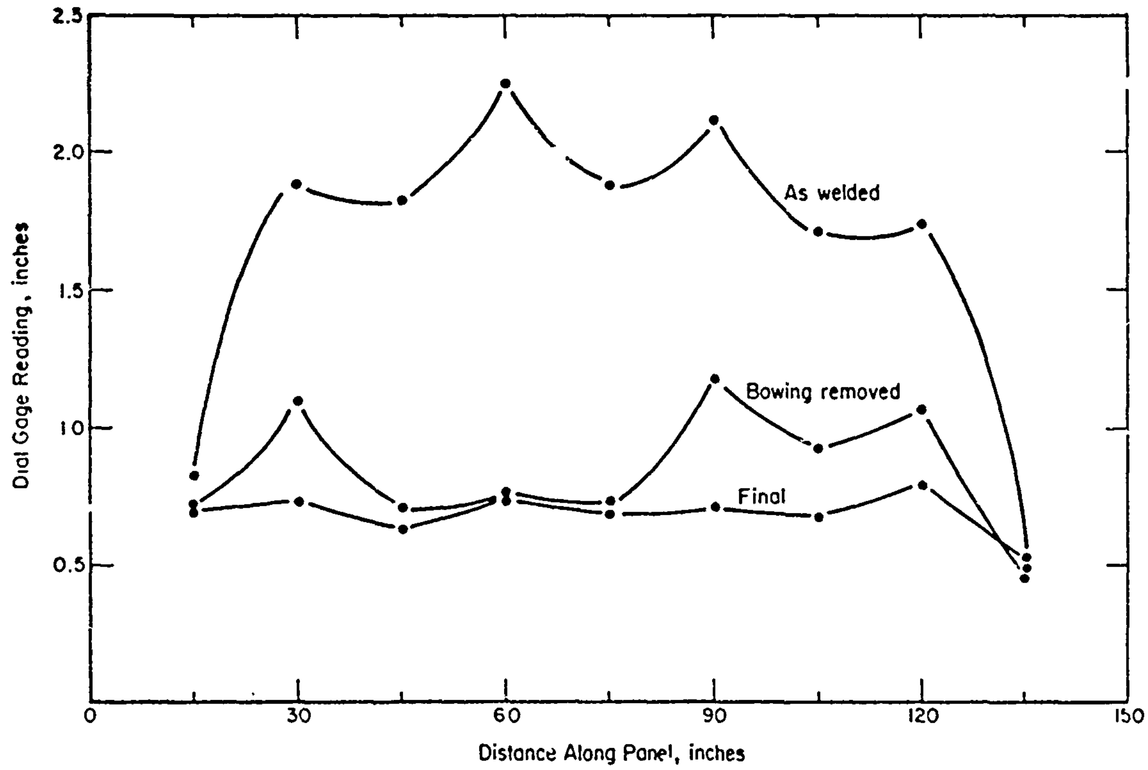

FIGURE 2. PANEL CONTOUR SHOWING EFFECTS OF FLAME STRAIGHTENING

FIGURE 3. FLAME STRAIGHTENING THE LASH PANEL AT AVONDALE

Conclusions of Laboratory Panel Work

The laboratory panel work showed that line heating could be used effectively in distortion removal. The principal features of the technique were to use a working temperature between 900 and 1050 F and to apply the quench continuously at a point approximately 2 inches behind the flame. All lines were at the high points which occurred in the region of the stiffener-to-plate welds on the opposite side from the stiffener.

The laboratory panel work also resulted in the training of Avondale personnel in the techniques for flame straightening quenched-and-tempered steel. This training was performed on panels of comparable size, thickness, stiffener spacing, and steel to those of the LASH ship to be straightened at Avondale by Avondale personnel in the subsequent phase.

SHIPYARD STRAIGHTENING

The shipyard straightening was done at Avondale on a LASH ship panel by Avondale production workers. The Battelle-Columbus investigator was present as an observer only.

The panel was essentially the same as that used in the laboratory experiments with respect to steel chemistry, plate thickness, and stiffener spacing. The principal difference is that the LASH panel was welded into the structure; whereas the laboratory panel had been free on the ends.

The general procedures developed in the laboratory were followed with respect to temperature range, temperature measurement, and placement of heating lines. The torch end had an annular quench surrounding the flame as shown in Figure 3 and was therefore different from the single-orifice quench used in the laboratory; however, this did not alter the procedures or the results.

Flame straightening was done entirely by line heating at the stiffener location on the reverse side of the plate from the stiffener. The torch speed was approximately 30 inches per minute; however, it was necessary to remove the torch periodically to check the temperature. It was found that the operator had no trouble maintaining the torch speed required to stay within the operating temperature range of 900 to 1050 F after a little practice.

The decision of when the straightening was completed was left entirely to the Avondale supervisor. After the completion of one line over each stiffener, he measured the distortion to be approximately 1/16 inch and halted the straightening at that point since the residual distortion was within acceptance limits. The as-welded distortion had been between 1/4 and 3/8 inch midway between stiffeners; so, 3/16 to 5/16 was removed by flame straightening.

Properties

The following segments were taken from the LASH panel and shipped to Battelle-Columbus for mechanical property evaluation:

(1) Plate which had been neither welded nor straightened

(2) Plate to which a stiffener had been welded but no straightening had been performed

(3) Plate to which a stiffener had been welded and flame straightened.

A total of 24 Charpy V-notch and 2 tensile samples were prepared from each of the three panel segments. The samples from the plates containing the double-fillet welds were prepared carefully to avoid introducing any effect of welding into the analysis. Each Charpy blank was etched to reveal the heat-affected zones, and the notch was placed between the heat-affected zones from each of the fillet welds. All samples were taken parallel to the rolling direction with the notch perpendicular to the surface. The results of these tests appear in Table 2. They show that the flame straightening did not reduce either the impact properties or the strength of the steel. The elongation was reduced slightly although this difference is not considered major.

Cost Savings

The working time required to flame straighten the 7-foot by 12-1/2-foot by 5/16-inch panel containing six stiffeners in this program was 40 minutes. Under the current regulations which forbid flame straightening of quenched-and-tempered steel, the only certain way to reduce the distortion to 1/16 inch or below is to remove the distorted panel and replace it with a new one. The estimated time required for this in the case of a 9-foot by 20-foot by 5/16-inch panel is broken down as follows:

TABLE II. PROPERTIES OF STEEL STRAIGHTENED IN THE SHIPYARD

Description	2/3 Size Charpy Results Upper Shelf (ft-lb)	+50 (F)	Tensile Results σ_y (ksi)	Elongation (% in 2 in.)	σ_T (ksi)
Base Plate	30	-178	85.2	21.0	100.0
Between fillets, not straightened	31	<-195	84.1	17.0	105.5
Between fillets, flame straightened	31	<-195	83.6	18.5	105.8

Removal

Burning periphery of bulkhead and stiffeners	3 hours
Arc gouging	6 hours
Grinding	6 hours
Removal by crane crew	2 hours
Shipfitters and marking	6 hours
	23 hours

Replacement

Shipfitters layout of plate and stiffeners	3 hours
Burning of plate and stiffeners	4 hours
Other service burning on reinstalling bulkhead	2 hours
Welding stiffeners to plate	8 hours
Installation of bulkhead by shipfitters	8 hours
Periphery welding	12 hours
	37 hours

Hence, removal and replacement of a 9-foot by 20-foot panel requires an estimated 60 man-hours and there is a chance straightening may be required again. Flame straightening required less than 1 hour.

Conclusions From Shipyard Work

Based on the progression of work described in this report, beginning with simulations and ending with a successful application in a shipyard, there is a strong indication that welding distortion can be removed from quenched-and-tempered steels by flame straightening with no unacceptable loss in mechanical properties. Furthermore, distortion removal by flame straightening is much more economical than any alternative.

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Mr. D. D. Phillips and Mr. John Masset of Avondale Shipyards, Incorporated, were responsible for the liaison and implementation of the shipyard portion of the program. Mr. W. Vachon of Bath Iron Works provided the labor estimates for the removal and replacement of the panel. The help of these gentlemen is gratefully acknowledged.

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SSC-239, *Wave Loads in a Model of the SL-7 Containership Running at Oblique Headings in Regular Waves* by J. F. Dalzell and M. J. Chiocco. 1973. AD 780065

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